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# Symmetric Analysis

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# PREFACE

This study was performed with central research funds. The IDA project team consisted of Dr. Richard E. Schwartz (Project Leader), Mr. Richard W. Carpenter, and Dr. Dennis F. DeRiggi. The IDA Technical Review Committee was chaired by Dr. David L. Randall, Director of the System Evaluation Division, and included Dr. Bertrand C. Barrois, Mr. James N. Bexfield, and Dr. Robert F. Richbourg. Their helpful comments are gratefully acknowledged.

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# I. SYMMETRIC SIMULATION AND ANALYSIS

The concept of symmetric analysis (SA)[1] is to conduct simulation experiments in which all initial conditions are the same for the two sides, except for one difference (or a small, controlled number of differences) whose effect is being investigated. This means that the terrain is symmetric, the forces are identical, the objectives of the two sides are the same, and the starting positions are the same—except for the one selected difference. It does not mean that symmetry is maintained once the experiment is underway.

The primary purpose of SA is to reduce the number of factors that may affect the outcome of a simulation. Limiting the number of variables is a standard analytic and experimental procedure, the goal of which is to better understand and quantify the effects of the variable(s) that remain. SA provides a precise analog of a controlled experiment and, therefore, should be a valuable tool in those instances in which it may be applied reasonably. The hope and the expectation is that this benefit may prove to be much greater than is immediately apparent. Terrain and mission asymmetries do not simply introduce single extraneous variables, which might be compensated for by doubling the number of runs. Instead, they may affect a battle or a combat system in ways that are unexpected and difficult to anticipate or understand. Carefully controlling the terrain and mission factors can allow analysts to isolate and understand both their effects and the effects of other factors and to allow the analytic community to build the cumulative body of knowledge that characterizes more rigorous disciplines.

In addition to these conceptual advantages, SA may require considerably fewer runs to achieve the same statistical confidence and offers other advantages in particular types of analyses.

The rest of this chapter illustrates potential uses of SA and describes some specific potential benefits and limitations. Chapter II describes the terrain database developed and used in the project. Chapter III illustrates the use of SA in a series of simple experiments, which examine several aspects of the behavior of ModSAF, a widely used DIS simulator of computer-generated forces. They are exploratory and illustrate

[1] Symmetric analysis was conceived originally by Frederick Young.

some ways in which SA might be used. Although all of the experiments involve ground combat, the concept of SA applies to air and naval engagements.

## A. SPECIFIC POTENTIAL ADVANTAGES

Some specific advantages of symmetric analysis include the potentials for statistical efficiency, the direct comparing of alternative simulations, and several others discussed below.

### 1. Statistical Efficiency

In some cases, symmetric analysis may offer the opportunity to compare two alternatives directly to each other, rather than to compare each to a common reference. The advantage would be that many fewer runs may be necessary in order to obtain statistically valid results. The reasons for this include the following:

- In a symmetric analysis, each run provides a comparison datum point between two alternatives; in a traditional analysis, two runs (each alternative against a standard enemy) are required for each comparison point.
- When using separate runs comparing two alternatives against a standard enemy, the random uncertainties are additive, so that two comparison points may be needed to achieve the same statistical confidence as one run that directly compares the alternatives.

Suppose, for example, one wants to compare two new tank concepts. The traditional procedure is to make separate sets of runs using each concept against the same opposing force and to compare the results. Using symmetric analysis, one set of runs would be made with opposing forces equipped with the alternative concepts. In each case, the measure of effectiveness (MOE) might be the difference in the number of armored vehicles lost by each side.

For the traditional procedure, the MOEs for each concept would be averaged over all runs, and the difference between the averages computed. In order to have confidence in the result, enough runs would be made to reduce the variance in the resulting measure to a statistically acceptable level. Using the subscripts t for traditional methodology, i to denote individual runs to be summed over, and 1 and 2 for the two-tank concepts, and assuming the same number of runs (n) are made for each concept, the measure of the difference $D_t$ between the two concepts is:

$$D_t = ( \Sigma D_{1,i} - \Sigma D_{2,i} ) / n$$

The variance of this statistic is $\sigma_t^2 = (\sigma_{1,i}^2 + \sigma_{2,i}^2) / n$, where $\sigma_{1,i}^2$ and $\sigma_{2,i}^2$ are the variances in the individual run measures $D_{1,i}$ and $D_{2,i}$ for concepts 1 and 2, respectively.

For the symmetric analysis with m runs (using subscript s to denote symmetric methodology), the measure of the difference between the two concepts would be $D_s = \Sigma D_{s,i} / m$, with variance $\sigma_s^2 = \Sigma\sigma_{s,i}^2 / m$.

If the variances $\sigma_\iota^2$ for all individual runs are the same and independent, then $\sigma_t^2 = 2\sigma_\iota^2 / n$ and $\sigma_s^2 = \sigma_\iota^2 / m$, so that $\sigma_t^2$ would equal $\sigma_s^2$ if n equaled 2m. Since two sets of n runs are made in the traditional case, four times as many runs would have to be made to achieve the same variance as a symmetric analysis.

There is no assurance that individual run outcome variances are the same for traditional and symmetric runs, and there are some cases in which this is unlikely. Consider weapon alternatives that do not engage each other directly, such as alternative shoulder-fired antiaircraft weapons. The linkage between a force's infantry defending against enemy aircraft and the same force's aircraft attacking enemy positions occupied by infantry is indirect at best. A scenario that includes both is likely to have largely independent battles, similar to running separate simulations for each. Putting the two battles in one run would result in half the number of runs, using twice the resources in each run. The MOE would be the difference in the MOE for each battle, with variance twice as large as each individual battle. There is no real advantage to running separate battles in the guise of one symmetric simulation.

For systems such as tanks that interact directly, it would be possible to use a traditional asymmetric scenario with two alternative concepts opposing each other. This would still not result in a direct comparison of two concepts, however. In any set of runs, it would not be clear whether a given result derived from the tank characteristics or terrain and mission characteristics. At a minimum, two sets of runs would need to be made, with each concept used on each side. If the results favored the same side in each set, the implication would be that terrain or mission characteristics were causal factors, complicating the comparison of the two concepts.

## 2. Comparison of Simulations

The degree of control possible in symmetric simulations may be of particular value in analyzing the performance of the simulation systems themselves. Examples within distributed interactive simulation (DIS) might include alternative semiautomated

forces (SAF) systems [e.g., Modular SAF (ModSAF) vs. JANUS-Link], SAF systems vs. manned simulators, or a system against itself (ModSAF vs. ModSAF analyses are discussed in Chapter III).

Training using opposing manned simulators in a symmetric setting might be effective as a competitive spur. If enough manned simulators are available, such training could improve the throughput of the training facility by training two units simultaneously.

While this approach may be used as a validation tool, it may be more valuable as a way to gain understanding and further simulation development. For example, SAF vs. manned simulator exercises might be used to:

- Measure the extent to which SAF behavior approximates that of manned simulators
- Identify the most important types of behaviors that were not simulated well, or not simulated at all, by the SAF system
- Identify situations (e.g., types of terrain) in which the SAF did not perform well
- Characterize the relative performance of the simulators
- Calibrate the SAF system (e.g., setting the expertise levels of simulated commanders).

For these types of purposes, the realism constraints of symmetric analysis may be quite acceptable. In fact, existing approaches to model verification and validation rely heavily on isolating particular aspects of the simulation, such as lower level performance characteristics. Lower level characteristics also need to be evaluated in a larger context to ensure that they collectively constitute a realistic simulation (e.g., tank gunner time delays and accuracy need to be part of realistic tank behavior during a battle). The particular advantage of symmetric analysis is that it offers the possibility of controlling the battle variables to the extent that anomalous behaviors may be identified and isolated easily.

### 3. Other

There may be other advantages to using symmetry to support particular types of analyses. Two that have occurred to the authors are:

- *Handedness*—A symmetric terrain would offer a unique ability to explore handedness (right/left) biases, either in simulations or in human operators.
- *Symmetry Within One Force*—One of the experiments described in Chapter III was a pincer attack. With symmetric terrain, the scenario was designed so that

pincers (and not the opposing forces) were symmetric. There may be other cases in which a symmetry within one force is useful.

## B. REALISM

Symmetric battles do not occur, and every symmetric analysis must suffer some lack of realism. However, all battle simulations suffer this lack to some extent. The issue should not be whether symmetric simulation can precisely represent the real world, but whether it can be used effectively to understand and evaluate battles and battlefield systems, especially human behavior.

Opposing forces may be similar but, in general, will have somewhat different systems (e.g., U.S. vs. Russian tanks). Clearly, symmetric analysis would not be used to evaluate weapons designed to operate against specific opposing characteristics (e.g., designed to penetrate the armor of T-80 tanks). In other contexts, fighting against an otherwise equal force may offer the best test of a system. In particular, command, control, and communications ($C^3$) systems are difficult to evaluate, and battles in which different force levels and weapons determine the outcome may not offer the best means of understanding $C^3$ effects.

Constructing scenarios with the same mission for the opposing forces is a significant problem. Four possibilities are offered here:

- *Meeting Engagements*—The mission might be scouting or moving to a location.
- *Control of Terrain Features*—The objective would be to gain control of key terrain. The forces might occupy symmetric hills and be tasked with occupying the other (while retaining control of the original). Another possibility would be to occupy and control a hill located on the symmetry seam.
- *"Trench" Warfare*—The objective would be to penetrate the opposing force while retaining control of one's own territory.
- *"Flag" Command Posts (Chess Kings)*—A flag vehicle would be designated and the objective would be to destroy the opponent's flag.

The realism of symmetric terrain is also limited. This is discussed in Chapter II.

## C. OBSERVATIONS

Symmetric analysis is not applicable when specific asymmetric factors, such as characteristics of enemy systems, are integral to the analysis. In other cases and in the long-term effort to build a cumulative body of knowledge, operational realism is less important than the ability to isolate and understand effects.

It is hard to prove, but the authors' intuition is that symmetric analysis will yield different and, in many ways, clearer understanding of the pros and cons of some systems. It is a new approach that provides a different and potentially valuable view of the choices under consideration. It should be easier to trace cause and effect in symmetric analysis than in traditional simulation setups in which the results depend on many differences other than the choice under consideration. For the example of competing new tank concepts, direct confrontation should dramatically highlight their relative strengths and weaknesses, even if either concept would defeat a current enemy.

Symmetric analyses may prove of particular value in man-in-the-loop experiments for analyzing command, control, communications, computers, and intelligence ($C^4I$). These systems do not usually operate against particular enemy characteristics and systems but should be effective against any enemy. They are notoriously difficult to evaluate, and directly competing alternative concepts may well provide improved understanding of their strengths and weaknesses.

It remains true that a scenario may favor one concept over another. The strengths of one concept may pay off more in the chosen scenario than the strengths of the other. However, understanding this scenario dependence may be easier in a symmetric setup, where the strengths and weaknesses of each concept confront one another directly and no other differences exist between the two sides.

# II. THE SYMMETRIC TERRAIN DATABASE

## A. CONCEPT AND POTENTIAL ANOMALIES

A key part of symmetric analysis is the construction of symmetric terrain. The basic idea is to reflect an existing terrain area around a boundary line. For digital databases defining flat terrain, this is a conceptually simple process. For other terrain, the process might be more complex, and choices for reflecting lines to simplify the process might be more restrictive.

If one reflection is good, are two better? If a rectangular terrain patch is reflected around a line (say, east-west), the resulting area could then be reflected around a perpendicular (north-south) line. This would create two axes of symmetry, so that a force could have an internal left-right symmetry in addition to being symmetric to the opposing force. This might be useful in specialized situations (perhaps in conducting a handedness analysis) but does not seem to have any generalized advantages. It would be more difficult to construct a terrain without obvious anomalies. This idea was not pursued.

A simple reflection may produce unrealistic terrain or anomalous features as a result of the discontinuity (in the derivative) along the reflection line. Some examples include:

- *Sharp Folds*—There will be a sharp crease on the reflection line. Terrain sloping up to it will have a ridge along the line, but terrain sloping down will have a valley. To a large extent, these effects are inherent in digitized terrain anyway. As described below, the terrain shape is defined by giving the elevation at regularly spaced lattice points, and the crease along the reflecting line is not basically different from the crease along any lattice line. However, the reflection line would have slope reversals at all points along it.
- *Roads, Rivers, and Other Curvilinear Features*—Curvilinear features crossing the reflection line at an angle other than perpendicular will have a sharp bend, producing various degrees of unrealism. The sharpness of the bend could potentially be changed by manipulating the database to change the path of the feature, but unnatural shapes might persist. For example, if the reflection line cuts across a bend in a road, intersecting it twice, then (depending on which part of the road is within the reflected area) the road will either become a

closed loop or will become two roads connected to the mirrored area but not connected to each other. Such behavior would be even more unnatural in a river, with the additional complication of flow direction.

- *Terrain Features such as Hills, Valleys, and Ridges*—Many types of topographic features could not be reflected along arbitrary lines and appear entirely natural. In most cases, the distortion would seem fairly benign, e.g., two symmetric valleys joining at an angle.

In summary, an arbitrarily chosen reflecting boundary is likely to create a symmetric terrain database that is quite unnatural in appearance. However, the choice of terrain for experiments on research and development (R&D) concepts and prototypes is not usually severely constrained. In this case, it should be possible to find a terrain data set that has adequate complexity but behaves properly near the selected reflecting boundary. Symmetric analysis of air or open-ocean naval engagements would automatically have symmetric "terrain."

## B. THE DEMONSTRATION DATABASES

The symmetric terrain database is a standard format S-1000 database representing a 20 km x 20 km region in which the northern and southern halves are reflections of one another. It was produced by Durwood Gafford of Lockheed-Martin (formerly, Loral Aerospace), Bellevue, WA (LADS, Bellevue). His work was supported by George Lukes of the Defense Advanced Research Projects Agency, who liked the notion of using symmetric terrain to conduct simulation experiments. The effort began in early spring of 1996 under the direction of Dale Miller at LADS Bellevue and was completed by mid-summer. Jeff Turner of the U.S. Army Topographical Engineering Center contributed in an oversight role.

The database was constructed by reflecting a rectangular portion of an existing terrain database across a pre-selected axis. A 20 km x 10 km section of the Hunter-Liggett Reservation containing enough topographical features to sustain interesting engagement scenarios was chosen as the area to be reflected. This section contains both the Stony Valley and the Lower Stony Reservoir. The southern boundary of this rectangle, the axis of reflection, intersects a series of commanding hills, which, arguably, might serve as objectives for forces in a symmetric engagement.

Figure 1, below, is a schematic diagram of the terrain database. The MIL GRIG coordinates are shown in the diagram. The southwest and northeast corners correspond to

UTM coordinates 10SFQ5000079500 and 10SFQ7000089500, respectively. The original 50 km x 50 km database referred to in Figure 1 is formally known as Hunter - 0110. It is shown in Figure 2 with the reflected rectangle highlighted.

Initially, in an attempt to save development time, an effort was undertaken to construct the symmetric terrain from a "run-time" database. After a few false starts, this strategy was abandoned, and the more standard procedure of constructing a source data file using the S-1000 Tool Kit was pursued. This approach led to the successful completion of the task. The resulting symmetric terrain database is shown in Figure 3. Format '4' and format '5' terrain databases were subsequently compiled from the S-1000 source file. These formatted databases permitted IDA to conduct symmetric analyses using ModSAF versions 2.0 and 2.1.

Finally, a visual, or "3-D out-of-window-view" database was constructed in November 1996 by Leo J. Salemann of Lockheed Martin Information Systems, Bellevue, WA. This database, also constructed from the S-1000 source file, is commonly displayed on the "Stealth Viewer" using the GT100 graphics engine.

```
4003000 ----------------------------------------------------
        |                                                   |
        |  original 50k x 50k Hunter Liggett (UTM zone 10S) |
        |                                                   |
        |                                                   |
        |          +          +          +          +       |
        |                                                   |
3989500 - - - - - - - - -|---------------------|            |
        |                |                     |            |
        |                |      10k x 20k      |            |
        |          +     | section of original |    +       |
        |                |                     |            |
3979500 - - - - - - - - -|---------------------|            |
        |                |/////////////////////|            |
        |                |///// reflected /////|            |
        |          +     |/////// area ////////|    +       |
        |                |/////////////////////|            |
3969500 - - - - - - - - -|---------------------|            |
        |                                                   |
        |                |                     |            |
        |          +          +          +          +       |
        |                |                     |            |
        |                                                   |
        |                |                     |            |
        |                                                   |
3953000 +----------------|---------------------|------------|
     635000           650000                670000       685000
```

**Figure 1. Hunter-Liggett Terrain Database Schematic Showing Reflected Area**

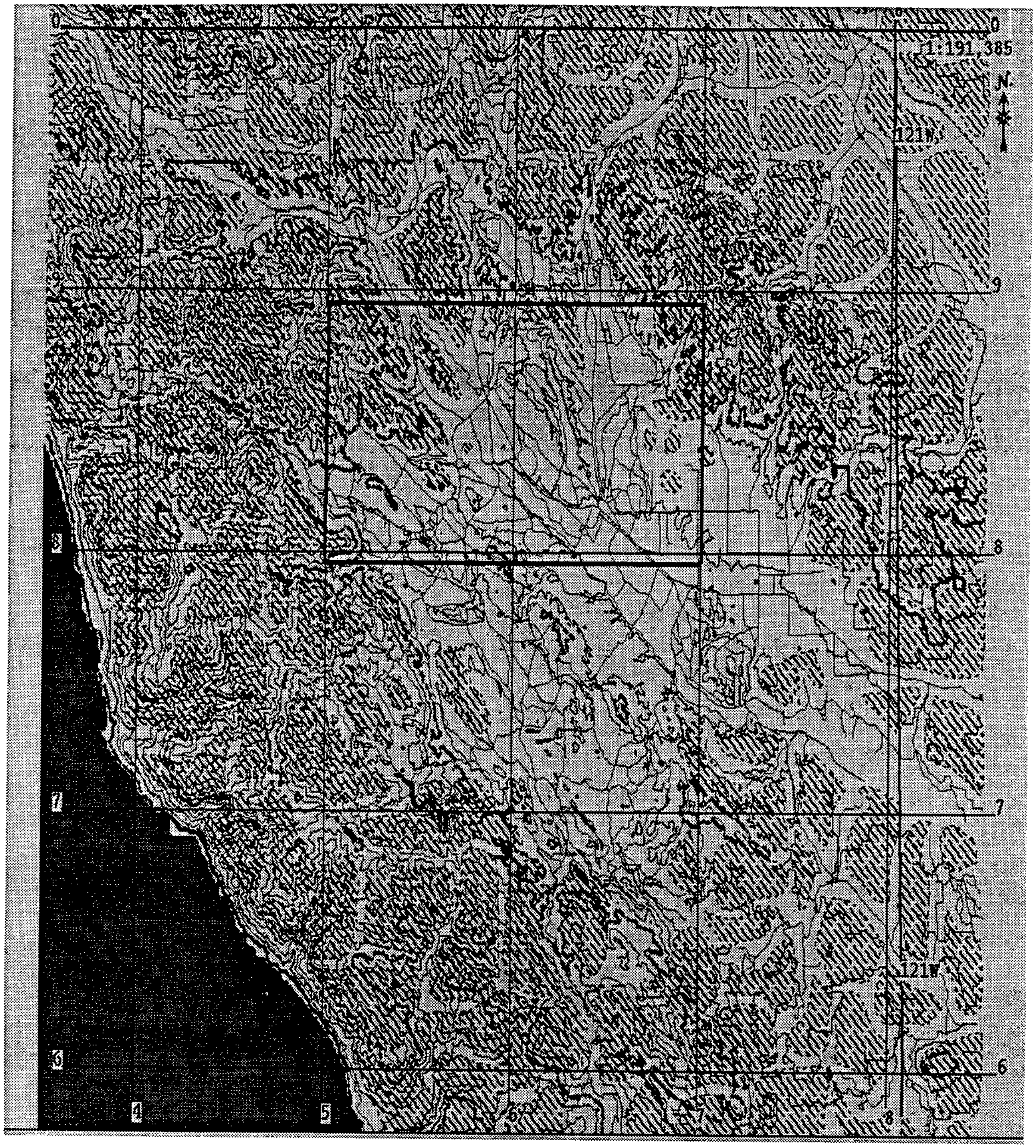


Figure 2. Hunter-Liggett Terrain Database (50 km x 50 km) with Rectangle (20 km x 10 km) Selected for Reflection

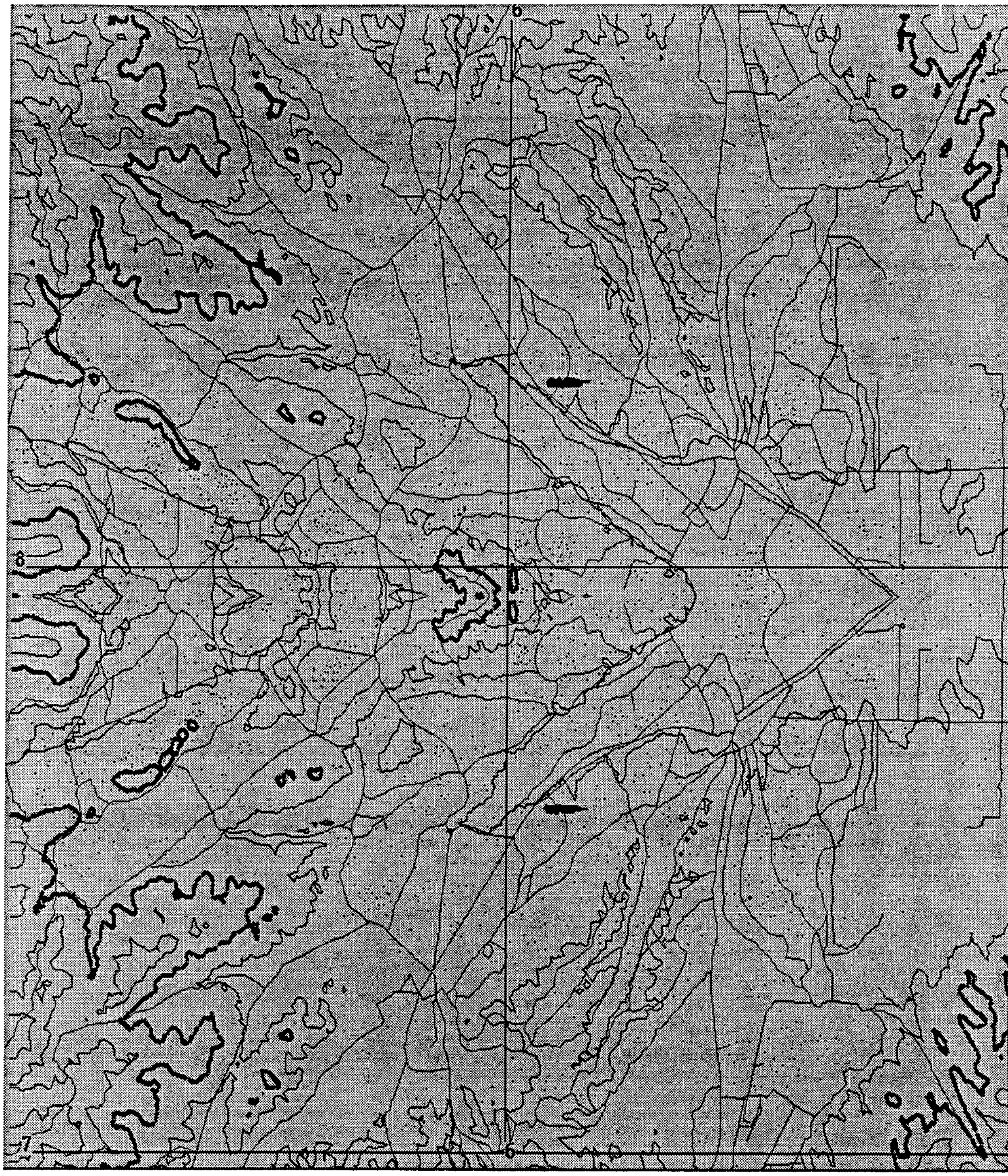

Figure 3. Symmetric Terrain Database (20 km x 20 km)

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# III. ANALYSES

The resources available for this task allowed a small series of experiments. The goals in selecting the analytic issues and defining the experimental parameters were, first, to test the new database and illustrate ways in which SA might be used and, second, to produce useful results. Exploring some aspects of ModSAF behavior and determining factors within the simulation that affected battle outcomes was judged to fit these criteria.

ModSAF is the most widely used DIS simulator of computer-generated forces because, by using it, a single operator can manage the simulation of numerous vehicles. The operator gives instructions concerning force size and characteristics and commands the forces by issuing orders such as the paths they should follow and engagement orders. ModSAF itself controls actual vehicle movement and firing decisions. The algorithms it uses are intended to conform to vehicle characteristics and military practice, but the complexity of behavior in a battlefield environment clearly presents a simulation challenge. Operators at IDA and elsewhere have observed unexpected behaviors and battle outcomes. SA is an ideal tool for controlling parameter variations and isolating factors that influence the results.

Rather than being completely planned in advance, the experiments were largely exploratory, with results from one set of runs suggesting further tests. Except for the force ratio tests, all tests used identical M1 tank forces on each side, typically with 14 or 16 vehicles. The experiments were

- *Terrain and Motion Dependencies*—These exercises were conducted on standard (asymmetric) terrain, with a force on an open plain attacking a force on ridges and hills, to determine which force had an advantage. Previous ModSAF experience indicated that the attacking force would have an advantage, which contradicts commonly accepted military tactical concepts.
- *Force Ratio Analysis*—These exercises were symmetric except for varying the size of the opposing forces to examine how losses varied with force ratio.
- *Synchronized Attack*—These exercises had a force conducting a pincer attack against the flanks of a force that thought it was moving to frontal contact. Each force was internally symmetric, with the symmetry used to precisely coordinate the movement of the pincers. In a variation, the attack was from

two sides but the defenders were arranged to face each attack. The objective was to examine the value of the coordinated attack.

- *Hull and Turret Orientation*—These exercises were variations of an attack from two sides with the defenders' tank hulls or turrets not facing the attack. The object was to determine the effects of orientation.
- *Other Investigations*—These exercises examined the relative performance of moving and stationary forces and the impact that firing the first shot of an engagement had on the outcome.

## A. TERRAIN AND MOTION DEPENDENCIES

In previous experiences with ModSAF, study team members observed the unexpected results that an armored force moving across a plain and attacking a stationary defensive force in hilltop positions seemed to have an advantage.

A series of initial runs were made using asymmetric terrain, and equal forces of M1 tanks with one force placed on ridges and hilltops and the other force attacking across an open flat area. Repeated trials confirmed that the attackers won consistently.

Next, defensive positions were carefully modified in an attempt to take better advantage of the terrain. The goal was to place the defenders slightly behind hill crests, so that they could see over the hilltops but were partially masked. Repeated trials were made with continuing slight position adjustments, until a set of positions was found that gave the defenders the advantage.

These trials were intended for learning and for qualitative assessment, and no numerical results are presented here. Some observations include

- The digital terrain database essentially consists of triangular flat areas pieced together. The database resolution affects the characteristics of protected positions (their number, locations, degree of protection, limits on intervisibility, etc.). In particular, the horizontal resolution for the Hunter-Liggett terrain data of about 125 meters and the relatively sparse representation of vegetation severely limit the terrain advantage of defensive positions.
- Finding protected positions using the ModSAF displays and tools is sufficiently difficult and time consuming that the authors believe it is not possible in a dynamic, live exercise. In the specific case examined, this represents a difference between ModSAF and either manned simulators (in

which each tank has a crew that can position it using a 3-D view) or actual tanks. And this difference significantly affects the battle outcome.

- Presumably, tanks in partially masked positions are harder to detect and hit. Other factors give the attackers the advantage when the defenders are in the open on hill faces:
  - Moving Target vs. Moving Shooter—Accuracy is degraded when the shooter is moving or when the target is moving. The formulas used in ModSAF give a $p_{hit}$ advantage to a moving tank shooting at a stationary target over a stationary tank shooting at a moving target.
  - Exposed Area—Tanks on an open slope may expose a significant part of their top surface to tanks on the plain.

## B. FORCE-LEVEL ANALYSIS

The objective of this analysis was to determine how initial differences in force levels affected the outcome of a battle. Four sets of runs were made in a single terrain area with 10 runs in each set and force ratios ranging from 1:1 to 2.33:1. In each set of runs, the Blue force consisted of an armor company (14 M1 tanks). The Red force varied, with the different sets having 14, 10, 8, and 6 M1s. The results are summarized in Table 1 and Figure 1.

**Table 1. Average Losses with Varying Force Levels**

| Number of Red Vehicles | Mean Blue Losses | Mean Red Losses |
|---|---|---|
| 6 | 2.4 | 6.0 |
| 8 | 4.1 | 7.9 |
| 10 | 7.1 | 9.2 |
| 14 | 9.1 | 10.8 |

These results are generally consistent with accepted knowledge (e.g., as predicted by the Lancaster equations) that favorable force ratios yield increasingly better outcomes.

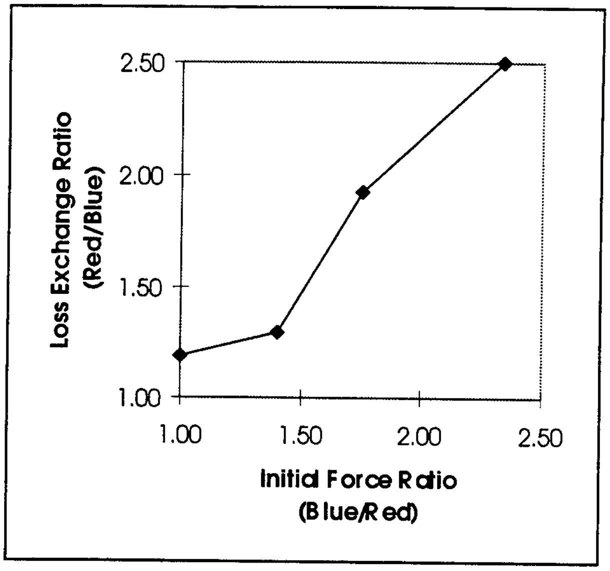


**Figure 4. Loss Exchange Ratio as a Function of Initial Force Ratio**

## C. SYNCHRONIZED ATTACK

Two sets of 16 runs each were made exploring the value of synchronized attacks from multiple directions. Figure 2 diagrams the two test scenarios. Each scenario used 4 platoons of 4 M1s, totaling a company of 16 M1s, on each side. The forces for each side were internally symmetric but not symmetric to the forces on the other side. In scenario 1, the four Red platoons move toward a hill occupied by Blue, and two of the Blue platoons come down the hill to meet them. Shortly after these forces engage, the remaining two Blue platoons conduct a coordinated pincer attack on Red's rear flanks. Each run was stopped after the last of the Red forces crossed a line near the hill. Scenario 2 used relatively flat terrain and all forces were stationary, with each platoon facing an enemy platoon. Runs were stopped after a set time (3 minutes).

The entering hypothesis for each scenario was that Blue should win most often. In scenario 1, the Blue pincer units attack broadside, thus having a greater and more vulnerable target cross section to hit. Secondly, the Blue force is dispersed, with each gun pointed initially in the general direction of the entire Red force, while the Red force is relatively concentrated with each gun initially pointed only at part of the Blue force. This could mean that a Red tank would have more difficulty finding targets and also would have to rotate its turret farther to engage targets (particularly after a number have been killed). In scenario 2, only the second factor applies.

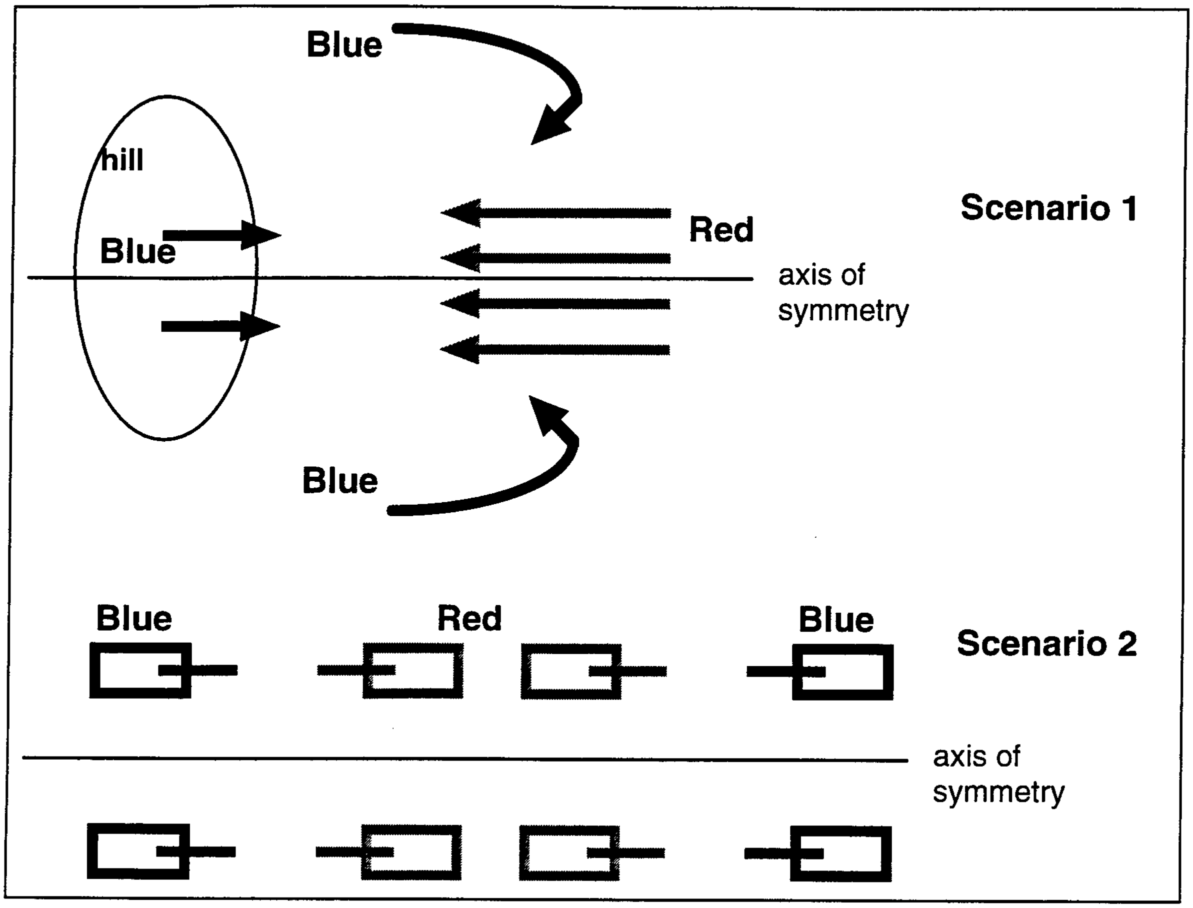


**Figure 5. Synchronized Attack Diagrams**

Table 2 summarizes the test results. Blue did better in scenario 1, but the sides were nearly equal in scenario 2.

**Table 2. Synchronized Attack Results**

| Scenario | Mean Losses | | Winners of Runs | | |
|---|---|---|---|---|---|
| | Blue | Red | Blue | Red | Tie |
| 1 | 7.31 | 9.56 | 12 | 3 | 1 |
| 2 | 11.19 | 11.00 | 8 | 6 | 2 |

## D. HULL AND TURRET ORIENTATION

The synchronized attack results presented in the previous section indicated that the Blue force had a significant advantage in its pincer attack. The scenario 2 results indicated the advantage did not derive from the dispersed disposition of the Blue forces. However, in each scenario the initial Blue forces encountered by Red were directly in front of them, so that any impact of having to rotate a turret to engage a target might be obscured.

Scenario 2 was used as a base case for further tests, with new sets of runs pointing the Red tanks' hulls, or the turrets, or both, at a 90° angle to Blue. Each set consisted of 16 runs, except that 24 runs were made in the set with hulls at 90° and turrets pointed at Blue. The variations are illustrated in Figure 3, and the resulting mean differences between Blue and Red losses are summarized in Table 3.

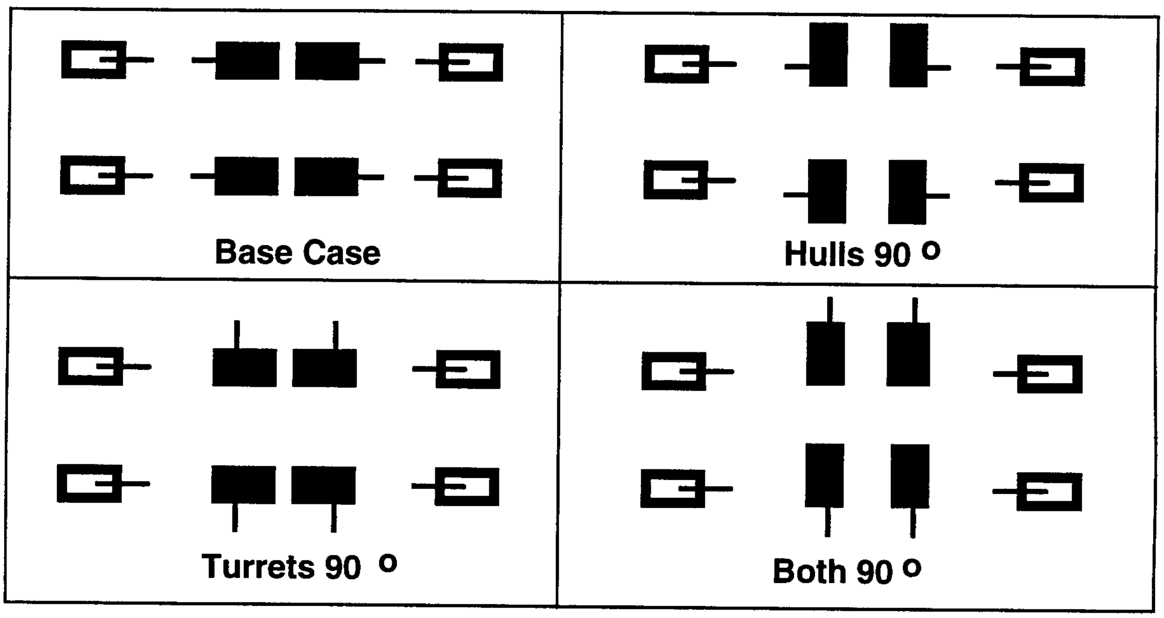


**Figure 6. Hull and Turret Orientations**

**Table 3. Mean Excess Red Losses for Different Orientations**

| Hull Angle | Turret Angle 0° | Turret Angle 90° |
|---|---|---|
| 0° | -0.19 | 1.69 |
| 90° | 2.96 | 3.88 |

Table 3 shows that Red losses increase when either the hulls or turrets are not pointed towards Blue, with the hull direction having the larger effect. This is a 2x2 factorial experiment, with 2 levels (0° and 90°) of each of the two factors (hull angle and turret angle). An analysis of variance shows the significance of the hull orientation below the 2 percent level, while the turret orientation effect is significant only at the 18 percent level (an effect this large would arise from random variations about 18 percent of the time). There was no significant interaction between the two effects; that is, within differences due to random variations, rotating the Red turrets increases the Red losses by about the same amount, whether or not the hulls are rotated.

## E. OTHER INVESTIGATIONS

The relative performance of moving and stationary vehicles was mentioned in Section A above but was not tested. Another factor of potential significance noted in conducting previously described tests is which side shoots first. This section describes investigations into these factors.

The first set of 20 runs investigated moving versus stationary vehicles and was designed to be as symmetric as possible. Each force was given the same fire permission range (2 km), and, at the time the moving force closed to this range, the positions were symmetric, in symmetric terrain (see Figure 4). Each side had 14 M1 tanks, and each trial continued until the forces closed to 0.5 km.

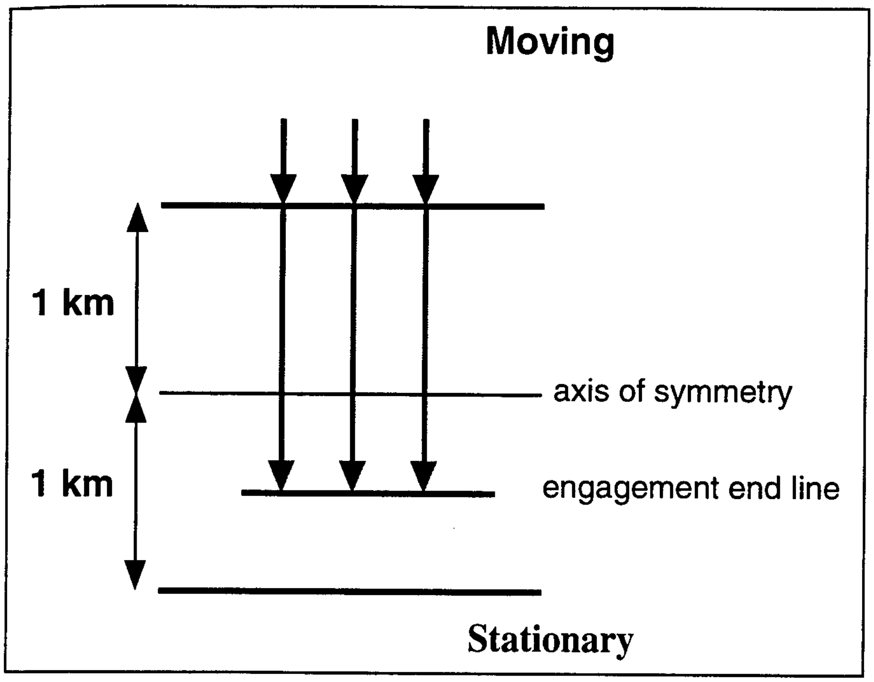


**Figure 7. Moving vs. Stationary Vehicles**

Table 4 summarizes the results of these trials. The moving force suffered fewer average losses and won most of the trials (where winning is defined as having fewer losses), and also shot first in 19 of the 20 trials. Using a paired comparison (t-test), the differences in losses between the sides with stationary and moving vehicles was significant at the 12 percent level. However, using the same test, the differences in losses between the side that shot first and the other side was significant at the 7.5 percent level. The initial hypothesis was that different outcomes would be caused by differences in the formulas used to compute hit probabilities for moving vehicles shooting at stationary targets and stationary vehicles shooting at moving targets. However, the results introduce the possibility that the advantage derives at least in part from the fact that, in these runs, the moving vehicles tend to shoot first, for unknown reasons.

**Table 4. Moving vs. Stationary and First Shooter vs. Not First Shooter**

| Average Losses | | | Winner (Number of Runs) | |
|---|---|---|---|---|
| Stationary | Moving | Difference | Moving | Stationary |
| 6.8 | 5.3 | 1.5 | 11 | 9 |
| 1st Shooter | Not 1st Shooter | Difference | 1st Shooter | Not 1st Shooter |
| 6.9 | 5.2 | 1.7 | 12 | 8 |

Further tests were conducted to examine the impact of shooting first. These were symmetric tests with 14 stationary M1s on each side facing each other 2 km apart, as shown in Figure 5. Sixteen runs were made, with Blue shooting first in seven, Red shooting first in eight, and essentially simultaneous first firing in one. In the trials in which Blue shot first, it averaged 0.28 fewer losses than Red. However, in the trials where Red shot first, it averaged 1.5 *more* losses than Blue. Overall, the first shooter averaged 0.67 more losses than the second.

These results indicate that, in the tests of moving versus stationary vehicles, the advantage for the moving vehicles was not due simply and directly to their frequency of shooting first. The greater probability of hit for a moving vehicle against a stationary target compared to a stationary vehicle against a moving target may account for much of the observed advantage. However, the consistent pattern of the moving side shooting first, and its strong correlation to the moving side's loss advantage, indicate that other factors may be significant. It may be, for example, in the moving versus stationary trials, that most of the moving vehicles shot before any of the stationary vehicles, but in the later stationary-vehicle trials, there was a more even mix.

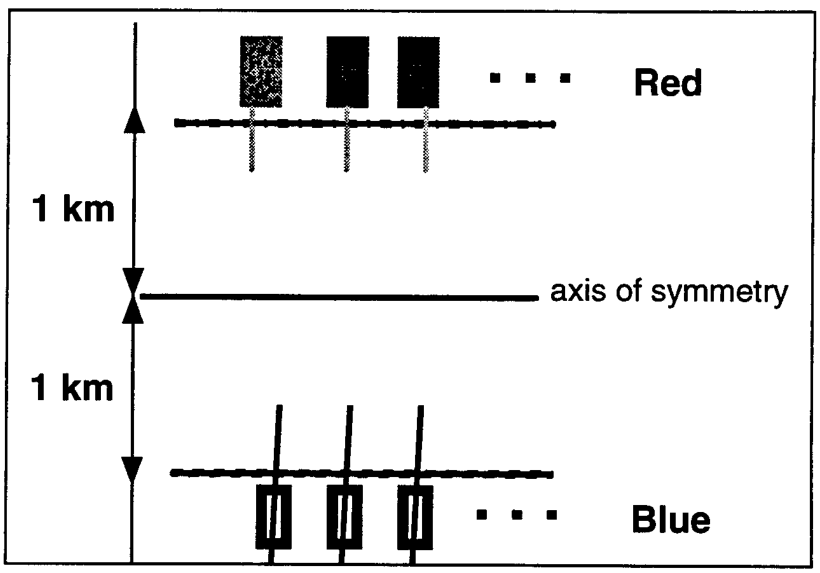


**Figure 8. Stationary, Symmetric Force**

The last series of tests attempted to examine why one side might tend to shoot consistently. Only two tanks were used in these tests, one stationary and one moving, as shown in Figure 6. Ten runs were made in which the stationary (Blue) vehicle fired first

nine times, and the two vehicles fired nearly simultaneously in the other. This is in contrast to the earlier results in which the moving vehicles tended to fire first.

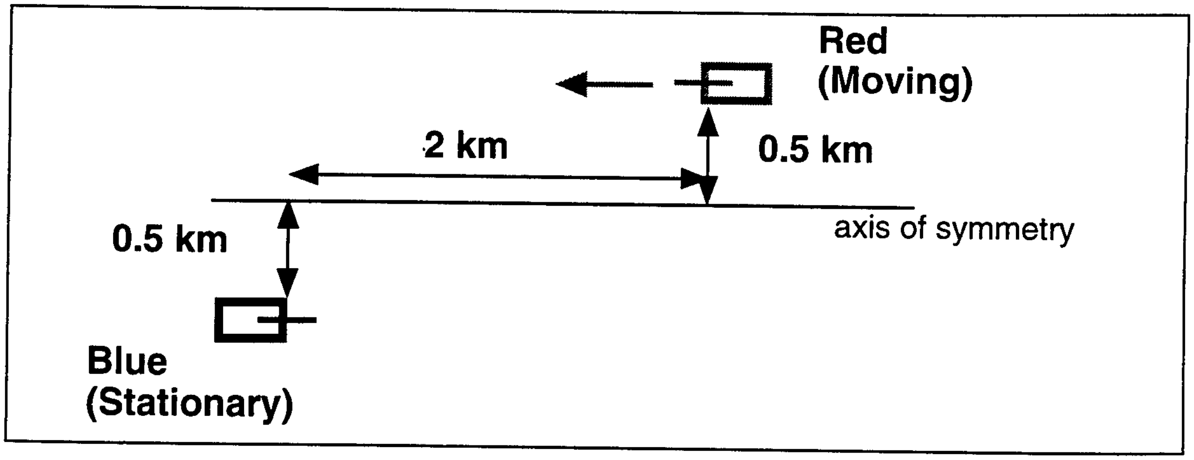


**Figure 9. Moving vs. Stationary, Two Vehicles**

Since only two vehicles were involved in these tests, it was fairly easy to see why the stationary tank fired first. As the Red tank started moving, its turret would swing from side to side over a wide (~135°) arc. The precession was essentially the same in each run, and, at the time the tanks reached their engagement range (1.7 km), its turret would be pointed well away from Blue. Blue's turret also precessed, but at the engagement range its turret would be pointed approximately at Red. Six additional runs were made with the engagement range changed to 2.1 km, which led to a geometry in which, at the engagement range, each vehicle's turret pointed approximately at the other. Each vehicle fired first in three of the six runs.

## F. PRELIMINARY FINDINGS

The purpose of this chapter is to illustrate the use of symmetric terrain and symmetric analysis. The most economical way to do this was to examine the "black-box" behavior of the ModSAF simulation. Symmetric terrain and symmetric analysis were consistently useful in setting up controlled experiments that isolated the effect of individual variables. Although very limited in scope, the tests that were conducted allow the formulation of some preliminary findings, as well as some unresolved issues, that may be worth further investigation.

Several results are consistent with expectations:

- The effect of initial force ratios on the loss ratio is generally consistent with expectations based on Lanchester equations.
- The effect of vehicle aspect is unsurprising. It is significantly disadvantageous to engage the front of enemy tanks while they are firing at the side of your tank.
- Initial relative turret orientation has a smaller effect, but the effect (in ModSAF) may be real.

The results of the first set of moving stationary trials seemed anomalous in at least one respect. The moving side shot first in 19 of the 20 runs. This result suggests that, at least with respect to shooting first, the trials were not independent. The subsequent one-on-one trials suggest that shooting first may be a function of the arbitrary, but largely deterministic, precession phases of the turrets. However, we did not do additional runs to rule out a positive correlation between movement and shooting first.

In terms of outcomes on these 20 runs, the moving side had a small advantage and the side shooting first had a somewhat larger advantage. We peeked into the black box and determined that ModSAF gives a probability of hit advantage to movers in engagements with stationary targets. In and of itself, shooting first may not convey a tactical advantage unless the relative precession phases strongly favor the side that shoots first. More runs would be needed to resolve these possibilities or develop other possible explanations. The foregoing interpretations do not consider the possibility that even when the forces are identical on both sides, ModSAF algorithms for friendly and enemy forces may be different. While we have no reason to believe this, it is certainly something that should be ascertained (by symmetric analysis?) in any further ModSAF investigation.

Finally, it is clear that, with more resources, symmetric analysis could be used in man-in-the-loop evaluation of $C^3$ systems. It could be also be used to evaluate weapons and other systems.

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Symmetric analysis is based on force-on-force simulations conducted on symmetric terrain, obtained by reflecting a rectangular digital terrain database around one of its boundaries. Many of the input variables (e.g., forces, starting positions, and mission objectives) are the same for both sides. Only the experimental variables are different. This document introduces the concept of symmetric analysis, describes its benefits, and illustrates its application.

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